

Evaluation of screen-printing techniques for embedding ECG sensors in medical devices

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Abstract—Heart rate monitoring is the most important indicator to evaluate the clinical status of a newborn during birth. Approximately 90% of newborn infants make the transition from the intrauterine to extra uterine environment without major complications; however, the remaining 10% of newborn infants require assistance during this transition. Heart rate monitoring is required for guiding further interventions in the event of complications such as the need for resuscitation.

In this work we evaluate the suitability of embedding electrometer-based-amplifier sensors employing novel screen-printing techniques into medical devices. We compare our results with traditional copper based wired electrodes. Our implementation was able to acquire electrocardiogram with enough signal to noise ratio, suitable for heart rate detection with a 1% loss of heart rate accuracy, compared with the copper-based electrodes. Our device has the potential to be embedded in devices for assisting births though heart rate monitoring.

Keywords— electrocardiogram, textile, electrode, electric potential sensor, medical devices, wearables.

I. INTRODUCTION

Heart Rate (HR) monitoring in new-borns needing resuscitation during the first minutes of life has been used as an indicator of early neonatal mortality and possible brain injury in those who survive. During birth, prompt and accurate HR acquisition is required to guide further interventions [1]. There are several established methods for HR detection ranging from manual techniques such as palpation and auscultation to technology-based approaches including electrocardiography (ECG), pulse oximetry (PO), Doppler ultrasound and forehead reflectance photoplethysmography (PPG) [2].

PO is a well-established method that has proved to be efficient for HR monitoring in adults. However, the main limitation of PO is that HRs under 100 beats per minute (bpm) in new-borns, especially preterm infants, are not consistently detected due to the weakness of blood perfusion. The time required for correct positioning of the probe takes around one or two minutes for its application [2]. Alternative technologies such ECG recording just require the electrode to make contact with the patient in close proximity to the heart, being able to detect its electrical activity up to four times faster compared with PO [3].

A fast and reliable method to monitor HR immediately after birth does not currently exist. Available technologies lack both accuracy and rapid application and have not been designed considering the human factors associated with neonates. This includes skin vulnerability, size and weight [4].

The electric potential sensor (EPS) is an electrometer-based amplifier insulating electrode that does not require galvanic contact with the body to acquire biopotential signals.

Instead it operates with displacement currents and the traditional electrode-skin interface is replaced with a dielectric material. This type of non-contact sensing offers many benefits over traditional silver chloride (AgCl) electrodes such as removing the need for interface pastes [3], rapid heart rate detection, high quality full ECG acquisition and the ability to take non-contact measurement of biopotentials. Our previous work has proven the clinical need of designing a HR detection system in the delivery room [2-3].

In this work, we evaluate screen-printing technology offering comfort and washability, and assess its suitability for embedding ECG sensors in a medical mattress for HR detection in the neonatal delivery room. EPS sensors are embedded in a cotton substrate connected to an analogue front-end using conductive ink signal traces. The system is evaluated through a HR detection algorithm running in an embedded system equipped with a visual display. This aims to provide fast and accurate HR diagnostic information to assist neonatal clinical staff.

II. MATERIALS AND METHODS

A. Prototype ECG sensing system

Fig. 1 shows functional blocks of the prototype ECG sensing system designed for neonatal HR detection.

It consists of a pair of electric potential sensors with a footprint of 10 x 10 x 2 mm connected to an analogue front-end. Signal conditioning is performed using differential instrumentation amplifiers, hardware filtering and an analogue to digital converter. The prototype acquisition system contains four discrete hardware filters and three software finite impulse response filters. Hardware filters were designed to be switchable with variable Q for the notch filters. Software filters are also switchable and customisable through the graphical user interface. This allows our system to be fine-tuned for the requirements of different settings (e.g. clinical, home use, laboratory) that experience different ambient noise characteristics. Software filters were coded in C++ avoiding any external dependencies to minimise system resource usage.

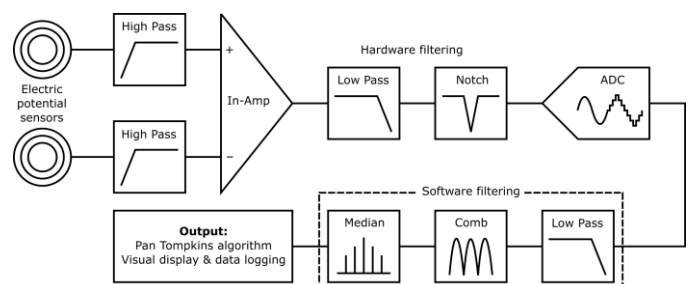


Fig. 1. Overview of real-time ECG sensing system (hardware implementation)

TABLE I. FRONT END FILTER DETAILS

Implementation	Type	f_c , Hz ^a	Operation
Hardware	High pass ($\times 2$)	0.05	Passive
	Low pass	200	2 nd order active
	Notch	50	2 nd order active twin-T, variable Q
Software	Comb	50	Forwards form
	Low pass	200	20 th order
	Averaging window	-	5 samples, variable

a. Corner frequency / frequency of interest

Table 1 shows the details of the filtering stages for both hardware and software implementations. Filter cut off frequencies were set to 0.05 Hz for high pass and 200 Hz for low pass. This was done to avoid any significant alteration on the ECG waveform including ST segment and T wave [5]. 50 Hz notch and comb filters were implemented to remove any unwanted power line interference noise.

Fig. 2 shows the experimental set up for testing screen printing techniques embedded in cotton substrate. The serial peripheral interface (SPI) output of the analogue to digital converter (ADC) is read by a quad-core ARM Cortex-A53 based platform which performs software filtering. A modified Pan Tompkins algorithm [6] for peak detection and HR acquisition was also implemented. This data is then logged and displayed in real-time on a custom touchscreen graphical user interface.

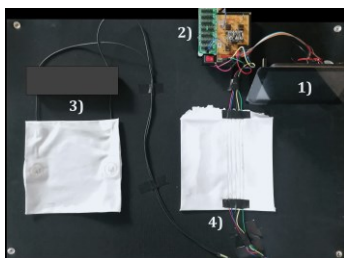
B. Electrode fabrication

The EPS sensing electrodes were embedded into the commercial neonatal delivery mattress. This requires the deposition of the grounding electrodes and conductive traces [7] on top of a cotton fabric substrate. The small footprint of our sensors does not pose the requirement of any redesign for this purpose. The EPS sensor is then placed behind the cotton as shown in Fig. 2, allowing for ECG recording. This also serves the purpose of protecting the delicate skin of the newborn in the proposed use case.

For embedding the sensors onto a mattress or garment, silver conductive traces (Fabink-TC-C4001) were screen printed onto the substrate and cured at 120°C for 10 minutes to evaporate unwanted solvents and improve conductivity, achieving a final resistance value of 43 Ω over an area of 340 mm² (2 mm x 170 mm traces). For comparison purposes copper-based EPS electrodes were also fabricated.

III. EXPERIMENTAL RESULTS

The goal of our experimental tests is to assess the suitability of using screen printing techniques for embedding ECG sensors on a neonatal delivery mattress. ECG Signal quality was evaluated to accurately detect HR. Three



- 1) ARM Cortex-A53 based platform & 7" Touch screen display
- 2) Analog front end
- 3) Silver conductive ink electrodes
- 4) Silver conductive ink signal traces

Fig. 2. Detail of prototype sensing system embedded in cotton substrate

experiments were conducted using both copper based electrodes and silver conductive ink-based electrodes.

- A) Evaluation of the ECG signal characteristics and validation of the filtering stages feeding the signal straight into our data acquisition stage.
- B) Evaluation using a neonate simulated mannequin providing the ECG signal using both the copper and silver conductive ink electrodes.
- C) Proof of concept demonstration for ECG detection in an adult volunteer.

A. Evaluation of ECG signal characteristics

Initial filter characterization was conducted using a reference ECG signal generated using a custom written LabVIEW program and a National Instruments DAQ with a 16-bit ADC. This consisted of a 2 V peak-to-peak (PP) generated ECG signal and 50 Hz noise injected directly into the front-end without the EPS sensors used for validation purposes. The frequency response of the hardware filtering block was derived using a Keysight Infiniivision oscilloscope, and the software stage was derived programmatically in C++. Fig. 3a shows the frequency response analysis of system prototype considering both hardware and software filters. As it is shown in Fig. 3b, the sensitivity of the electrometer-based amplifier sensors collects the 50 Hz power line interference, thus requiring a large capacity of frequency specific notch filtering to be available.

Fig. 3b shows the power spectral density (PSD) analysis considering both filtered and unfiltered ECG signal. As it is shown the unfiltered signal contains three main features: a concentrated power within the 1 to 40 Hz region corresponding to the ECG signal (i.e. the information used for heart rate estimation) [8]. This is followed by the powerline interference noise located at 50 Hz and its harmonics.

B. Evaluation using a neonate simulation environment

ECG signal acquisition was performed using a neonate simulation environment. We generated an ECG signal

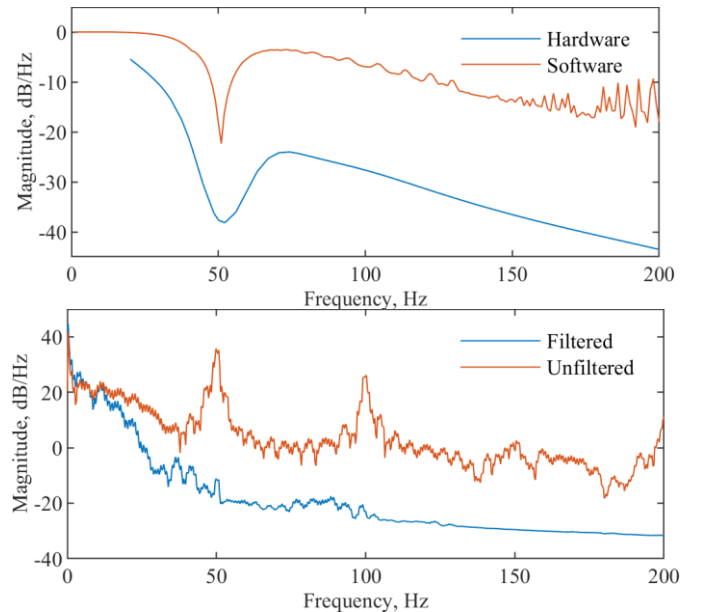


Fig. 3. a) Frequency response analysis of system (top) and b) Power spectral density of test signal (bottom) for a generated test ECG signal injected directly into the analogue front end.

employing our premature infant mannequin with an internal antenna (3 cm^2) for broadcasting the ECG signal of 200 mV PP with 50 Hz noise at 50 mV PP across an air gap of 2 cm to the sensors. This was employed to test the ECG signal quality of both copper and conductive silver ink implementations. Fig. 4 shows the signal development as it passed through the hardware and software filtering stages. As it is shown the combination of both hardware and software filters improves signal quality of both scenarios (4c, 4d). Additional ambient 50 Hz noise from the surrounding environment was also detected. No attempt was made to shield our device as the final goal will be to use the device within a neonatal intensive care unit which is typically an electrically noisy environment.

Fig. 5 shows the ECG signal reproduction for a single generated heartbeat using both copper and silver ink electrodes compared with the reference signal. As it is shown the copper electrode implementation showed accurate signal reproduction, with detailed ECG features reproduced (P, Q, R, S, T segments). In contrast, the silver conductive ink electrodes still presented unwanted noise after passing through the filtering stages. Both electrodes were able to reproduce the R peak, however the P and T waves are indistinguishable when using the silver ink electrode.

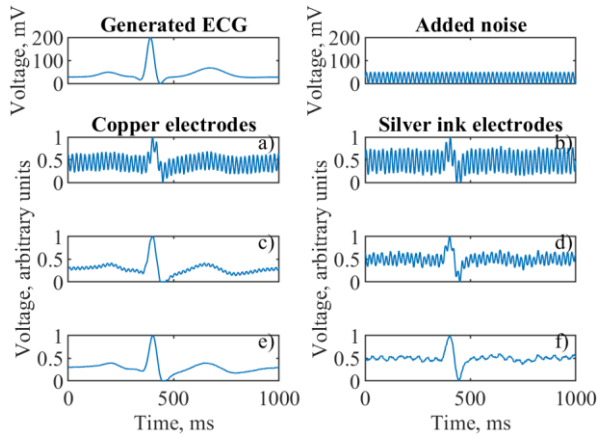


Fig. 4. Signal development as it passes through filtering stages, (a,b) unfiltered signal, (c,d) hardware filtering only, (e,f) hardware & software filtering considering both copper and silver ink electrodes

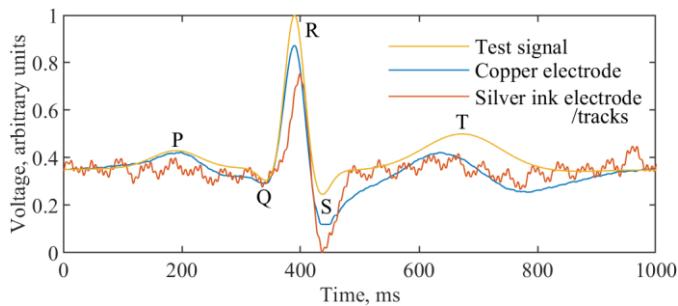


Fig. 5. Signal reproduction for a single generated heartbeat, annotated with PQRST features of the ECG for both copper and silver ink electrodes

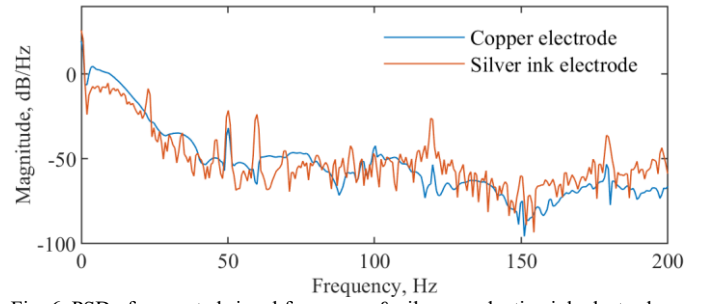


Fig. 6. PSD of generated signal for copper & silver conductive ink electrodes

Fig. 6 shows the PSD for the generated ECG signal after hardware and software filtering. The signals acquired using both types of electrodes are in agreement with our initial tests carried out injecting the ECG signal directly to our acquisition and filtering stages (Fig. 3). Both electrodes showed a peak corresponding to 50 Hz noise, however, as expected with the silver conductive ink it had a higher amplitude being consistent with the visible noise shown in Fig. 4f. The amplitude of the signal contained in the 5 – 15 Hz frequency range is also reduced for the silver conductive ink electrodes which we expect to affect ECG signal quality. Despite this, we aim on validating to what extent this will affect the HR extraction and determine whether the presented screen-printed implementation is suitable for embedding our EPS sensors within a garment/mattress.

C. Human volunteer proof of concept

ECG data was taken from an adult volunteer at rest in a sitting position using both the copper electrode and silver conductive ink embedded sensors. In our final test considering a human participant, it is important to consider additional effects affecting the acquisition. This is the case of movement artefacts/baseline wander which will be present when there is a requirement of performing resuscitation procedures in the new-born.

To account for this, a high pass filter ($f_c = 0.05 \text{ Hz}$) was used to remove the baseline wander from the signal, which serves for two purposes: to reduce distortion of the ECG waveform and to reduce the overall peak to peak amplitude of the signal allowing for exploitation of the entire range of the ADC. Fig. 7 shows the effect of the high pass filter on the recorded ECG signal from the adult volunteer. The baseline wander is reduced up to 6 times (from 12.5 arbitrary units (AU) to 2 AU) for the copper electrode, while for the silver conductive ink electrode there is a 4 times reduction (from 20 AU to 5 AU).

Both copper and silver conductive ink electrode signals are flattened by the HP filter. Despite the HP filtering, movement artefacts are still visible in the silver conductive ink electrode. With movement artefacts still present in the signal it is important to quantify the accuracy of the HR measurement to validate our sensor implementation on a neonatal mattress.

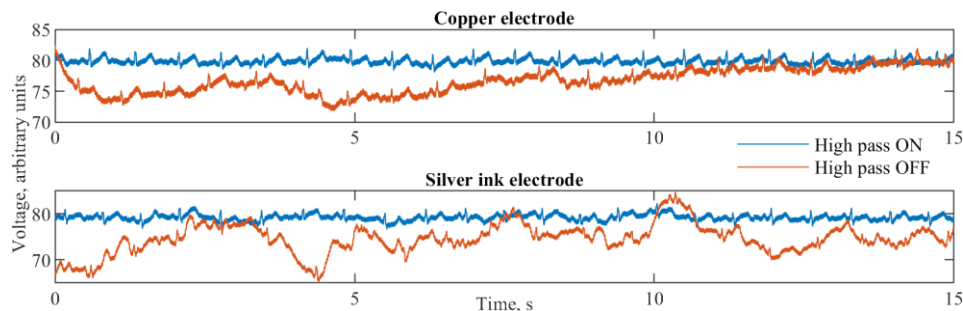


Fig. 7. Baseline wander and artefact removal by high pass filtering of a human ECG for copper and textile silver conductive ink electrodes

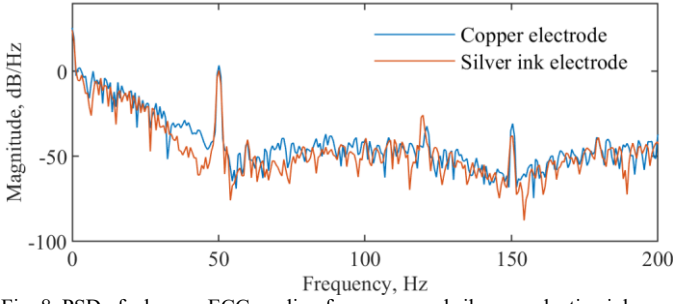


Fig. 8. PSD of a human ECG reading for copper and silver conductive ink electrodes

Fig. 8 shows the PSD analysis results of the human proof of concept tests for both the copper and silver conductive ink implementations. Although 50 Hz noise is still detected in both electrode types, the silver conductive ink electrode showed a marked loss in power between 30 to 45 Hz, showing an alteration in the ECG signal waveform (shown in Fig. 10) compared to the copper electrode.

Finally, to determine the feasibility of employing screen-printed silver conductive traces for accurate HR detection, we used as a metric the signal quality for HR detection. This is defined as the beat detection confidence using Eq. (1)

$$\text{Detection confidence} = 1 - \left(\frac{FP + FN}{N_{\text{peaks}}} \right) \quad (1)$$

Where FP = False positives, FN = False negatives recorded by the Pan Tompkins algorithm, and N_{peaks} = number of genuine peaks counted by manual inspection of the waveform. This was used to quantify the signal quality for the purposes of HR extraction.

Fig. 9 shows a segment of 7 seconds taken from a 60 second human ECG reading. Data shows consistent beat-to-beat waveform reproduction, and the R peak of each beat is represented with sufficient signal quality for accurate HR estimation. This was verified by implementing the Pan Tompkins algorithm generating a detection confidence from Eq. (1) of 99% and 98 % for the copper and silver ink electrodes respectively.

Fig. 10 shows a single beat for both electrode types. The silver conductive ink electrode still shows evidence of motion artefacts, particularly in the 500 – 600 ms segment. In comparison to the generated signal in Fig. 5, however, the silver conductive ink electrode showed enhanced signal reproduction in contact mode (as opposed to the scenario when the sensor is separated by an air gap), as its waveform more closely matches the waveform acquired through the copper electrodes.

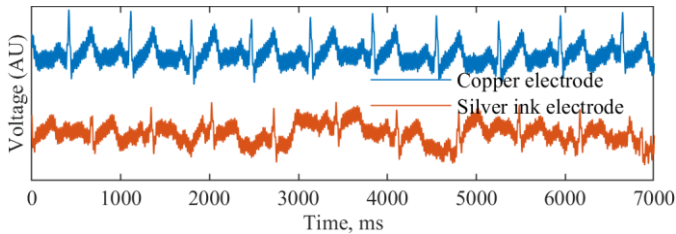


Fig. 9. Comparison of 7 seconds of filtered human ECG for silver conductive ink and copper electrodes

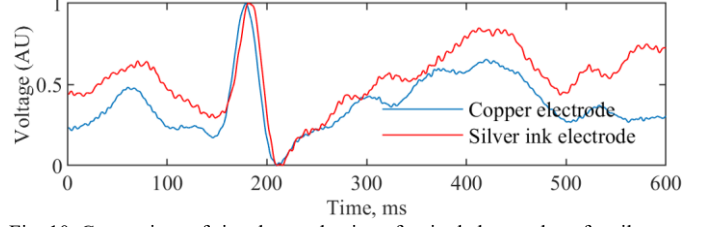


Fig. 10. Comparison of signal reproduction of a single human beat for silver conductive ink and copper electrodes

IV. CONCLUSIONS

In this paper, we have evaluated the use of screen-printing techniques for embedding ECG sensors within a neonatal mattress.

A proof of concept demonstration in human and simulated neonatal mannequin were conducted. Results showed that our system is able to record high quality electrocardiograms in a noisy environment similar to the neonatal intensive care unit. The effectiveness of the filtering stages provided 30 dB / Hz attenuation of 50 Hz noise reduction. The implemented filtering stages accounting for the case when movement artefacts are present was able to reduce the baseline wander up to 80%. Our results demonstrate that using silver conductive ink for embedding our EPS sensors into a mattress, it is possible to reproduce ECGs detailed features including P, Q, R S and T segments. Silver conductive ink was found to be suitable for ECG signal detection and HR calculation. Our results show that such implementation provides 98% detection confidence compared to a 99% when using wired copper-based electrodes.

Further work will investigate the implementation of shielding layers to mitigate 50Hz interference.

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